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Theoretical analysis of quantum dot amplifiers with high saturation power and low noise figure

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Abstract *Semiconductor quantum dot amplifiers are predicted to exhibit superior characteristics such as high gain, and output power and low noise. The analysis provides criteria and design guidelines for the realization of high quality amplifiers.*

Introduction

The dominance of the Erbium Doped Fibre Amplifier (EDFA) in optical communication systems, owes to their higher output power and lower noise figure (NF) compared to semiconductor amplifiers. Quantum Dot (QD) lasers have improved immensely the past few years and now exhibit properties like low threshold current density and high output power [1]. However, there has been only little work on QD amplifiers, perhaps owing to the small modal gain, requiring long waveguides, which is traditionally known to lead to strong Amplified Spontaneous Emission (ASE) saturation. We show here, that QD amplifiers may operate in an EDFA-like regime, with improved characteristics compared to bulk and Quantum Well (QW) amplifiers, despite the longer waveguides. Due to differences in fabrication method, material composition etc., the QD parameters may vary significantly, and we, therefore, perform an extensive analysis of key parameters, extending earlier work [2].

The model

The analysis is based on a detailed rate equation model, which previously has been shown to agree well with measured gain dynamics [3]. Full account of propagation effects is taken, including ASE. Carriers are assumed to be injected directly into the Wetting Layer (WL) and then relax through the Excited State (ES) of the dots into the Ground State (GS) through a combination of phonon and Auger processes. Thermal carrier excitation and escape from the dots ensure that the system will reach the correct thermal equilibrium given sufficient time. Effects like spectral hole burning and Fermi blocking are inherent parts of the model.

Basic device properties

The fundamental properties of QD amplifiers are first illustrated by presenting results for a reference device, which will serve as the starting point for the following analysis of the importance of different key parameters. For this purpose, we have chosen an InAs/GaAs device, with device parameters found in the literature. The gain spectrum under full inversion (proportional to the effective density of states of the device) is illustrated in Fig. 1(b), together with the gain spectrum for the current density of $1.75 kA/cm^2$ used for all results presented here. The structure is seen to exhibit an inhomogeneously broadened GS transition, an ES transition, and a WL in the shape of a QW. Key parameters include: maximum modal gain $22.5 cm^{-1}$ (GS), $36.5 cm^{-1}$ (ES), and $117 cm^{-1}$ (WL), low waveguide loss of $2 cm^{-1}$ [1], phonon dominated carrier capture time of $1 ps$, and a maximum Auger dominated intra dot relaxation time of $150 fs$ [3]

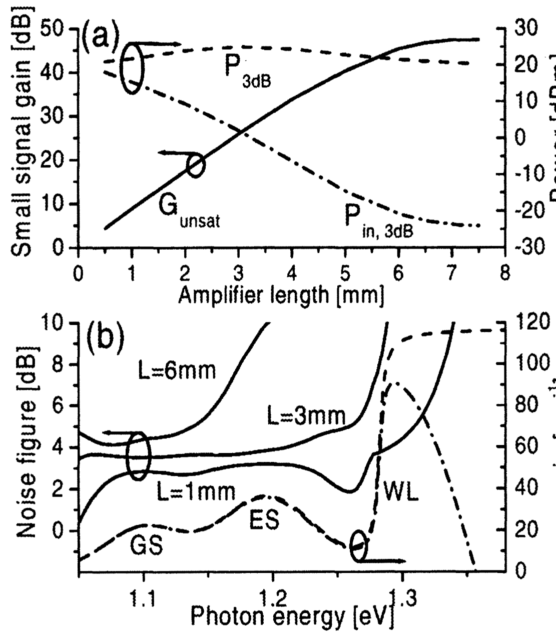

Fig.1: *(a) Small signal gain and input and output power required to reduce the gain by 3dB. (b) Noise figure for different device lengths and gain spectrum under full inversion (dashed line) and for a current density of $1.75 kA/cm^2$ (dash-dotted line).*

Fig. 1(a) illustrates the length dependence of the small signal gain, and saturated (3dB) output power, P_{3dB}, of the reference device. As in bulk and QW devices, the gain saturates due to ASE, but in this case at a much slower rate due to the small modal gain, which leads to a high maximum small signal gain of $47.5 dB$. The saturation length is on the order of $6 mm$, which is much longer than for a bulk/QW device. Also the saturated output power is seen to be very high, in the range of 20-$25 dBm$ for all lengths. The high P_{3dB} is a result of the combination of low modal gain, resulting in a low stimulated recombination rate locally, and the comparatively fast carrier capture and relaxation, resupplying the active states. It is the combination of low modal gain and high P_{3dB}, which causes the slow saturation from ASE and hence allows the large small signal gain.

The NF of the device as function of photon energy is shown in Fig. 1(b). At the centre of the GS transition (where the optical signal is injected), the NF is seen to increase from below 3*dB* (L=1*mm*) to 4.4*dB* (L=6*mm*). The fact that the noise figure is below the ordinary lower limit of 3*dB* simply reflects the small total gain of the 1mm device [4]. The remarkably good noise properties result from the high GS inversion, even at low WL densities. As the ASE starts to saturate the amplifier, the GS inversion decreases, resulting in a rapid increase of the noise figure beyond the saturation length.

Parameter variation

Lowering of the maximum GS modal gain to 14cm^{-1} (solid circles in Fig. 2) implies a slower increase of the small signal gain with length, and hence a longer saturation length. Secondly the device exhibits a higher P_{3dB} due to the smaller stimulated recombination rate locally. The higher P_{3dB} in turn leads to higher tolerance towards ASE and hence a higher maximum obtainable gain, on the order of 50*dB*. Finally the smaller modal gain leads to a slight increase of the NF compared with the reference device for lengths between 2 and 5*mm*, due to the increased relative importance of the waveguide losses. For devices longer than 5*mm*, the NF of the reference device increases rapidly due to ASE saturation, which decreases the inversion, whereas the device with small modal gain is far from ASE saturation and thus exhibits a better NF in this region. The improved NF is, however, at the cost of a much lower total gain and when compared at the same gain, the device with the highest modal gain exhibits a smaller NF in all cases.

By increasing the waveguide losses to 10cm^{-1} (triangles) the P_{3dB} is lowered by a few dBm compared to the reference device, which leads to a smaller maximum gain of the device. However, the NF increases strongly because the modal gain is now only twice the waveguide losses. It is thus essential to reduce the waveguide losses in QD amplifiers with small modal gain in order to avoid an unacceptably high NF.

Realization of fast carrier capture and relaxation is also essential, as evidenced by the results for either slow capture (open squares) or slow intra dot relaxation (open circles) of 20*ps*. In both cases the effect is seen to be a significant reduction of the P_{3dB}, most severely for the latter of the two. Again the lower P_{3dB} leads to a shorter saturation length and hence a lower maximum gain. It is thus important that QD injection dynamics are fast enough to sustain the rate of stimulated emission from the dots, leading to a high P_{3dB}.

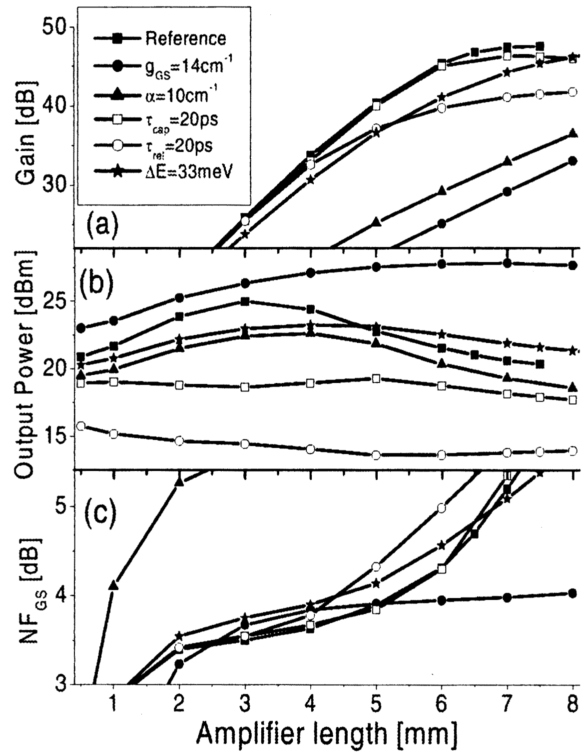

Fig. 2: *Small signal gain (a), saturated output power, P_{3dB}, (b), and noise figure at the centre of the GS transition (c) versus amplifier length for 6 different devices.*

The energy separation between GS, ES, and WL governs the extent of QD inversion relative to the WL occupation. The effect of reducing the level separation (marked with stars) is seen to be a sub-linear increase of the gain with length, because the GS population is strongly influenced by the rapid ASE saturation of the upper levels exhibiting higher modal gain. This also leads to a smaller P_{3dB}. In general, the level splitting of the dots should be as large as possible and certainly larger than the thermal energy in order to avoid the limitation arising from the ASE saturation of the upper levels.

Conclusion

We have shown that QD amplifiers can be expected to exhibit superior performance regarding small signal gain, saturated output power and noise figure. Furthermore, we have provided criteria and design guidelines for the realization of such devices.

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